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Transformation archetypes in global food systems

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Abstract

Food systems are primary drivers of human and environmental health, but the understanding of their dynamic co-transformation remains limited. We use a data-driven approach to disentangle different development pathways of national food systems (i.e., ‘transformation archetypes’) based on historical, intertwined trends of food system structure (agricultural inputs and outputs and food trade), and social and environmental outcomes (malnutrition, biosphere integrity, and greenhouse gases emissions) for 161 countries, from 1995 to 2015. We found that whilst food systems have consistently improved in terms of productivity (ratio of output to input), other metrics suggest a typology of three transformation archetypes across countries: rapidly expansionist, expansionist, and consolidative. Expansionist and rapidly expansionist archetypes increased in agricultural area, synthetic fertiliser use, and gross agricultural output, which was accompanied by malnutrition, environmental pressures, and lasting socioeconomic disadvantages. The lowest rates of change in key structure metrics were found in the consolidative archetype. Across all transformation archetypes, agricultural greenhouse gases emissions, synthetic fertiliser use, and ecological footprint of consumption increased faster than the expansion of agricultural area, and obesity levels increased more rapidly than undernourishment decreased. The persistence of these unsustainable trajectories occurred independently of improvements in productivity. Our model underscores the importance of quantifying the multiple human and environmental dimensions of food systems transformations and can serve as a starting point to identify potential leverage points for sustainability transformations. More attention is thus warranted to alternative development pathways able of delivering equitable benefits to both productivity and to human and environmental health.

Introduction

Industrial agriculture arose as a defining feature of global food systems, revealed by increased total crop yields and higher yield per input at scale. Important advancements in skills, technology, infrastructure, and trade led to increased food productivity (i.e., output in terms of weight or energy of food per unit of input invested - Benton & Bailey, 2019) and enabled the expansion of global, interconnected food supply chains. The widespread premise of prioritising yields and cheaper food to improve human nutrition, however, has recently been under scrutiny due to its detrimental effects to sustainable development (Lindgren et al., 2018; Sukhdev, 2018). From the perspective of the Sustainable Development Goals (SDGs) framework, numerous synergies and trade-offs exist between the 17 goals and 169 targets for human well-being, economic prosperity, and environmental protection (Pradhan et al., 2017). Arguably, food systems are the entity that primarily connects good health and wellbeing (SDG 3), sustainable consumption and production (SDG 12), and life on land (SDG 15 - Pradyumna, 2018).

Global food systems have been failing to deliver adequate diets for everyone: an increasing prevalence of 9% of the global population is undernourished whilst, paradoxically, obesity currently affects more than 13% of individuals (FAO et al., 2020) and roughly 1/3 of all food is lost or wasted (Aschemann-Witzel, 2016). Around 87% of all countries worldwide exhibit the coexistence of insufficient or excessive forms of malnutrition (Development Initiatives, 2020), and diet is the number one risk factor for mortality and morbidity worldwide (Afshin et al., 2019). In parallel, from production to consumption, food is responsible for 34% of anthropogenic greenhouse gas emissions (Crippa et al., 2021; Poore & Nemecek, 2018) and about 70% of freshwater use (Whitmee et al., 2015). Agriculture is the prime driver of the transgression of biosphere integrity and biogeochemical flow (e.g., nitrogen deposition - Campbell et al., 2017) and, in turn, is the sector most affected by these transgressions (IPCC, 2014). To move away from these trajectories, it is of paramount importance to analyse the systemic patterns of change of food systems as an entry point to the identification of potential leverage points for sustainability transformations (Abson et al., 2017; Oliver et al., 2018).

Transformation of global food systems

The investigation of the complex and dynamic interactions driving the sustainability and efficiency of food systems from input to output remains a challenge (Hadjikakou et al., 2019; TEEB, 2018). Food research is often fragmented across academic disciplines and sectors, and production or consumption stages tend to be studied in isolation from one another (Campbell et al., 2016; Dornelles et al., 2020). If metrics of health, equity and sustainability are not embedded in a more comprehensive framework of food systems efficiency (i.e., ‘the number of people that can be fed healthily and sustainably per unit input invested’ - Benton & Bailey, 2019), a narrow focus on increased productivity has the potential to accelerate detrimental effects for planetary and human health in an increasingly connected world (Bahadur et al., 2018; Bengtsson et al., 2018; Seppelt et al., 2020; Willett et al., 2019). Critically, a clearer understanding of the magnitude and direction of trade-offs between food systems’ productivity and key metrics is sorely needed for sustainability transformations (Fears et al., 2019; Nyström et al., 2019; Oliver et al., 2018; Pradhan et al., 2017). One way to achieve this, as we present in this study, is via an integrated model using standardized indicators to capture the multiple dimensions of food systems.

Whilst a focus on productivity of food systems has been elevated to a protagonist narrative (e.g., the claim that the world will need to produce 70% more food by 2050 has assumed unexpected traction - Alexandratos & Bruinsma, 2012; Benton & Bailey, 2019; Sukhdev, 2018), more holistic development pathways of multiple, co-transforming environmental and social outcomes in global food systems are often unquantified. Such social-ecological links related to food tend to be reported either in the form of states or trajectories. The state of multiple environmental, social and economic indicators across food systems have been measured cross-sectionally at different times and spaces (Chaudhary et al., 2018; Zurek et al., 2018) by the impacts of specific food types (Clark & Tilman, 2017; Poore & Nemecek, 2018; Springmann, Clark, et al., 2018), and/or by estimates of future production hotspots or of potential mitigation measures for biosphere integrity (Springmann, Clark, et al., 2018; Zabel et al., 2019). In contrast, longitudinal studies track variables through time and so offer a means to connect cause and effect, and to study trajectories. This approach has been used previously to study transformation pathways of food systems for pre-defined groups of countries (e.g., by areas of free trade or level of development - FAO, 2017), for quantifying the costs and economic returns of distinct agricultural models (Ruttan, 1977), for the exploration of mechanisms behind agricultural transitions (e.g., interactions between population growth and urbanization - Cumming et al., 2014), or for national food indicators of socio-economic access, biophysical capacity, and diversity of production (i.e., ‘resilience indicators’ - Seekell et al., 2017). As the availability of rich longitudinal datasets increases, so does the opportunity to: 1) gain an empirical understanding of intertwined rates of change within and across national food systems; 2) quantify the direction and magnitude of structure and outcome metrics under a comparable methodology; and thus to 3) specifically capture and compare the transformational feature of food systems.

Methods

Overview

Our data-driven approach to identify patterns of transformation (i.e., ‘transformation archetypes’) in global food systems analyses historical trends of structure metrics including agricultural inputs, outputs, and trade, and their relationship to outcomes including biosphere integrity, malnutrition (i.e., obesity and undernourishment), and greenhouse gases emissions in 161 countries, from 1995 to 2015. 'Transformation archetypes', in our study, reveal categorisations of patterns of incremental change that are suggestive of specific transition pathways, and the trajectories that these processes suggest or point to in terms of futures that may or may not be sustainable. This approach integrates statistical methods often used in ecology (e.g., cluster analysis and dissimilarity matrixes - Charrad et al., 2014) with macroeconomic measurements of trend analysis (e.g., Compound Annual Growth Rate; expressed as % of annual change and reported as median and interquartile range). Our analysis assumes broadly constant compound temporal rates, which is supported by an additional analysis of five-year intervals to explore potential short-term spikes. Our approach to map the resultant archetypes of food system change with respect to co-transforming environmental, social, and economic outcomes is valuable to help to investigate intertwined empirical links, track the speed of progress towards desirable social-ecological goals, and also reveal watchpoints to potentially mitigate risks associated with the existing undesirable trajectories of change (Dornelles et al., 2020).

Our analysis of transformation archetypes in global food systems consisted of three main stages (Supplementary Figure S1): 1) Data acquisition – extensive review and search; 2) Data preparation – standardization and duration filters applied; and 3) Data analysis –

trend analysis, cluster algorithm, significance testing, and analysis of five-year intervals. All steps in data preparation and analysis were conducted in the software R version 3.6.1.

Data acquisition:

We conducted an extensive search of publicly available repositories and official databases for comprehensive structure and outcome metrics expressing multiple aspects of agricultural production, food security and biosphere integrity related to food systems (Supplementary Table S1). Our design enabled a comparative assessment of the paradigms of interest: structure metrics are widely used as measurements of increased production (cf. *paradigm of productivity*), whilst the combination of structure and outcome metrics were here used to assess their links to productivity (cf. *paradigm of systemic efficiency*). A simplified framework of structure and outcome metrics and their connections in our integrative model is shown in Figure 1.

Structure metrics expressed different aspects and practices related to agricultural production as a whole and related indicators of socioeconomic access, as follows: input (composed by agricultural area, synthetic fertilizer use, and agricultural employment), output (represented by gross agricultural output), productivity (quantified by Agricultural Total Factor Productivity Index), and economic metrics (constituted by food imports, food exports, and Producer Price Index of agriculture). Structure metrics, as such, reveal means to achieve the ultimate function of food systems (i.e., feeding people) or are related to them as drivers or elements. Outcome metrics accounted for specific and non-specific impacts of food systems products and/or activities in respect to biosphere integrity (expressed by the Red List Index), land-system change (covering forest area and Ecological Footprint of Consumption), malnutrition (composed by prevalence of adult obesity and prevalence of undernourishment), and greenhouse gases emissions (including agricultural GHGE, land-use change and forestry GHGE, and the sum of agricultural, forestry, and other land-use – AFOLU GHGE; Supplementary Table S1). Outcome metrics, in this sense, express direct food-related goals for human and planetary health, proxy quantifications of such goals, and/or potential externalities from food practices. Socioeconomic indicators were represented by income category, GDP per capita (expressed as nominal and purchasing power parity), and the Human Development Index (expressed as index and category).

Data criteria for acquisition included attributes for length (minimum of 100 countries), time series (minimum of 10 years of measured observations, preferentially on a yearly basis), and relevance to multiple food systems stages. Twelve databases were explored from which 36 different metrics were acquired, respecting these selection criteria and described in more details in the Supplementary Tables S2 and S3. Metadata for all metrics are available in the Supplementary materials.

Data preparation:

The metrics acquired were subsequently collated into a hierarchical (i.e., individual variables, derived variables, and aggregate indicators) and standardized format by ‘country’, ‘year’, and ‘value’ for the longitudinal analysis. Instead of using conventional units for the state of a metric (e.g., hectares for spatial coverage, % of employment for agricultural work, or indexes for aggregated indicators), we expressed our data as annual change rate to enable a normalised comparison between distinct metrics and to specifically capture the transformational element of food systems (more details in ‘trends analysis’). An exception to this approach was used for socioeconomic indicators explored in our study which, in terms of practical relevance, are categorical (e.g., income category and Human Development Index category) and cannot be expressed in % of annual change.

We took precautions to prevent double-counting across the different hierarchies of our structure and outcome metrics. For structure metrics, we investigated how the patterns of change of raw (e.g., agricultural area) and proportional variables (e.g., agricultural employment) helped to explain wider patterns of change in one aggregate indicator in which they are embedded (e.g., productivity, TFP). All structure metrics were previously scaled and tested for correlations before the analysis of rates of co-transformation across countries (more details in 'cluster algorithm'). For outcome metrics, we explored the links between the emergent development pathways found across countries with changes in: a) specific food-related impacts (e.g., malnutrition); b) externalities tied to changes in structure metrics (e.g., biosphere integrity), and c) different components of such pressures (e.g., agricultural GHGE, land-use change and forestry GHGE, and AFOLU GHGE).

The filters and duration analysis were conducted for each metric in two steps: a) an initial filter designed to collate the metrics which met the initial criteria for acquisition (data for ≥100 countries and ≥10 years of observations) after the standardization stage; and b) a refined filter programmed to extract maximum number of countries with comparable durations (i.e., number of years) and periods (i.e., in a similar time coverage) across the remaining metrics following the initial filter, covering at least 80% of the possible maximum duration for that respective window of time (see Supplementary materials; Supplementary Tables S4 and S5). In other words, the refined filter of best fit analysis was intended to assemble the metrics by the most reasonable chronological consistency, and thus avoid anachronic comparisons in duration (e.g., comparing the annual growth rate of 12 years of measured observations of one particular country with 40 years of data points of a different country) or period of coverage (e.g., juxtaposing the annual growth rate of one country from 1961 to 1981 with another country from 1991 to 2011).

Data analysis:

Our data analysis consisted of four steps: (a) trend analysis, (b) cluster algorithm, (c) significance testing, and (d) analysis of five-year intervals.

(a) Trends analysis:

The trend analysis was designed to assess the patterns of transformation per year in all structure and outcome metrics across countries. Following the filter of best fit indicated in the data preparation stage, the timeframe for evaluation and comparison of metrics was stipulated for the period from 1995 to 2015. In our model, we adapted the widely used equation of compound annual growth rate to estimate annualized trends in all metrics (Prajneshu & Chandran, 2005). Whilst there might exist legitimate foundations for criticism on the use of empirical models assuming linear change over time (Paine et al., 2012; Prajneshu & Chandran, 2005) we understand that the adjusted equation and subsequent analysis of five-year intervals sufficiently address any potential limitations of our approach. In addition, the use of the adjusted compound annual change rate can facilitate comparison amongst multiple metrics which show varying longitudinal paths while enabling a standardized expression of change across numerous countries. The adapted equation of compound annual change rate, expressed as % of annual change (reported in the results as median and interquartile range), was calculated taking into account the median of the first five *starting values* and the last five *end values* in order to prevent undue weight of first and last years:

$$End\ value = \ median\ (last\ five\ end\ values)$$

$$Start\ value = \ median\ (first\ five\ start\ values)$$

$$CACR = \left(\frac{End\ value}{Start\ value}\right)^{\left(\frac{1}{End\ value\ (Year)\ -\ Start\ value\ (Year)}\right)} - 1\ \times\ 100$$

(b) Cluster algorithm:

The cluster analysis computed patterns of co-transformation in five key structure metrics: agricultural area, synthetic fertilizer use, agricultural employment, gross agricultural output, and Agricultural Total Factor Productivity. These five metrics were included as the key structure metrics because of their: a) key importance to assess the input and production stages of food systems from the paradigm of productivity; b) relative low variance in comparison to other structure metrics (e.g., expressed by current monetary units); c) well-established use across different disciplines in the food literature to assess different components and the efficiency of agricultural production (i.e., ratio of output per unit of input – productivity); and d) independence (i.e., no strong pair-wise correlations were identified for the rate of change between all the five structure metrics – all Pearson’s correlation scores < 0.6).

Due to substantial variation in contextual drivers and states of the five key structural metrics of food systems across countries globally, we investigated potential similarities in their longitudinal change using a cluster analysis approach to be able to identify transformation archetypes. For this purpose, we used the R package NbClust (Charrad et al., 2014), which estimates the most appropriate clustering scheme and determines the number of groups for a set of different objects. The cluster algorithm runs 30 indices simultaneously, in addition to hierarchical clustering with different distance measures and aggregation methods and obtains the final result by varying all of their possible combinations. Before running the cluster analysis, we scaled the compound annual change rate of the five key structural metrics by their respective median and median absolute deviation and tested for collinearity to minimize the potential dominance of a particular set of metrics over others due to its magnitude, unit, or range. Finally, the metrics were merged into the same data frame by their scaled compound annual change rate values and only the countries with existing values for all five key structure metrics were included in the assessment by the cluster algorithm (leading to 161 countries in total). To generate the cluster dendrogram, the Euclidean distances of the dissimilarity matrix across all possible ordering of observations (2^{n-1}) were used as input for the hierarchical cluster method (Ward2), which agglomerated the tightest cluster scheme possible and placed observations in order by the square root of the weighted sum of their squared distances.

(c) Significance testing:

Following the allocation of countries into different groups of transformation archetypes provided by the cluster analysis, we tested for statistical differences across groups for all structure and outcome metrics by an analysis of variance model, after the implementation of the Shapiro-Wilk test of normality. Tukey’s honest significance test was applied to scrutinize differences between specific groups. Statistical significance threshold was set at 0.05.

(d) Five-year intervals analysis:

As a final step, we assessed the potential for non-linearities in the temporal trends of the food system metrics used in our analysis to influence allocation of transformation archetypes. To this end, we computed the compound annual change rate of all structure and outcome metrics of each transformation archetype in sub-divided periods of five years: from 1995 to 2000; from 2000 to 2005; from 2005 to 2010; and from 2010 to 2015. Here, however, we used the conventional compound annual change rate equation of real end and start values for each five-year interval (and not the median of the first five start values and last five end values) due to the low number of observations in each interval. Goodness of fit statistics were calculated to explore potentially more appropriate cluster composition (guided by the same absolute number of clusters reported in the main results from 1995 to 2015). Within and across cluster distances (Ward2) were extracted and the cophenetic distance was calculated to express goodness of fit (correlation between Euclidean distances in the dissimilarity matrix and the agglomeration output from the hierarchical cluster, Ward2). The cophenetic distances were broadly similar in the five-year intervals and in the main interval from 1995 to 2015 for the three transformation archetypes assessed.

Results & Discussion

Archetypes of change

We identified three transformation archetypes in global food systems metrics from 1995 to 2015, as described in Box 1: 1) rapidly expansionist transformation archetype (RETA), 2) expansionist transformation archetype (ETA), and 3) consolidative transformation archetype (CTA). Evidence for the existence of three distinct transformation archetypes emerged more consistently than any other clustering across 30 different clustering indices tested (see Methods), with significant differences in trend metrics between the clusters supported by a post-hoc ANOVA analysis (Supplementary Tables S6 and S7). In mapping the archetypes, we found coexistence of the three distinct transformation archetypes in neighbouring countries from South America, Sub-Saharan Africa, and South-western and South-eastern Asia (i.e., broad geographic regions are not homogeneous but show all three identified archetypes in close proximity; Figure 2). Other regions such as North America, Western Europe, and North Asia tended to be more homogeneous, mainly composed by CTA. More detailed results are available in the Supplementary results, from the interpretation of the cluster algorithm’s output (Supplementary Figures S2, S3, S4, S5, and S6) to five-year intervals analysis (Supplementary Figures S7 and S8), along with individual country profiles. Below is a high-level summary of the key results.

Agricultural productivity

Our analysis suggests substantial progress from a perspective of food production and agricultural cost-efficiency over the past two decades. Increase in Agricultural Total Factor Productivity was evident across all transformation archetypes, identified by similar annual rates of change reported as median and interquartile range (in between brackets): RETA = 0.82% (1.56%), ETA = 1.2% (2.16%), and CTA = 1.36% (1.29%). Agricultural area, synthetic fertiliser use, and gross agricultural output displayed the largest rates of annual change in RETA followed by ETA then CTA (with exception of synthetic fertiliser use, which showed similar trends between ETA and CTA; Figure 3). Importantly, no distinctions were found across transformation archetypes in terms of agricultural area at the beginning of the analysis, expressed by percent of total land composed of agriculture: RETA = 32.44% (11.98%), ETA = 39.98% (12.23%), and CTA = 42.45% (14.38%), suggesting that trends are independent of starting baseline of the archetypes. Agricultural employment was under the steepest annual reduction in CTA, declining -3.11% (1.79%) per year, and decreased further in RETA, -1.16% (1.62%), than in ETA, -0.65% (1.07%). Agricultural Total Factor Productivity was the only metric amongst the key structure metrics to show no differences across the three transformation archetypes, increasing at a rate of approximately 1% per year. This progress in productivity is widely assumed to bring wider socioeconomic benefits (Benton & Bailey, 2019; Matsuyama, 1992), however, our analysis shows it does not reliably reflect achievements across food systems in terms of environmental sustainability, overcoming coexistent forms of malnutrition, or improvement of socioeconomic wellbeing (Benton & Bailey, 2019; Matsuyama, 1992; Seppelt et al., 2020).

Environmental outcomes

Concurrent with the highest rate of increase in agricultural area, RETA exhibited the greatest magnitude of change in agricultural greenhouse gases emissions (GHGE), and ecological footprint of consumption, followed by ETA, whilst CTA tended to indicate comparative stability at high absolute impact levels (Figure 4). RETA and ETA displayed increasing rates of agricultural GHGE of 2.42% (1.87%) and 1.01% (1.68%), respectively, whilst CTA expressed virtually no change (despite showing decreasing rates of agricultural area). Ecological footprint of consumption increased more rapidly in RETA – 3.05% (1.47%) – in comparison to CTA – 0.99% (3.08%). Two metrics had unclear overall changes due to high variability across countries from 1995 to 2015 (GHGE from land-use change and forestry and from Agriculture, Forestry and Other Land Use – AFOLU; Supplementary Tables S6 and S7). The CT archetype manifested a slow increase in forest area of 0.12% (1.07%) – the only environmental outcome with a higher rate of change than RETA and ETA.

The Red List Index exhibited slow decrease averaged across all transformation archetypes of roughly -0.3% per year. More comprehensive assessments of biodiversity relevant to food and agriculture (e.g., pollinators, coral reefs, and soil-dwelling organisms) have reported substantial declines in vital ecosystem services over past decades, but comprehensive country level data are lacking (Beckmann et al., 2019; Pilling et al., 2020).

Given the evidence of excessive chemical inputs in disrupting biogeochemical cycles (Campbell et al., 2017; Fowler et al., 2013), it is important to note the steady, high use of synthetic fertilizer in CTA and its steeply increasing use in RETA (and to some extent in ETA). CTA used an order of magnitude more synthetic fertiliser in absolute value in 1995 than ETA, and two orders of magnitude more than RETA: CTA = 2.2 x 10^5 (9.5 x 10^5) tonnes, ETA = 2.3 x 10^4 (16.3 x 10^4), and RETA = 9 x 10^3 (3.8 x 10^4). Thus, our analysis reveals an absence of environmental pressure alleviation in CTA (with exception to a slow increase in forest cover) in combination with rapid agricultural intensification and expansion of agricultural area (strongly implicated in habitat loss and biodiversity decline - Schipper et al., 2020) in RETA, and to a slightly lesser extent in ETA. Collectively, these patterns unfold a worrying picture of the negative environmental impacts of recent global food system transformations.

Malnourishment

Yield growth and agricultural intensification have been widely encouraged to nourish a growing global population (Alexandratos & Bruinsma, 2012; Benton & Bailey, 2019), yet we found this paradigm has had only partial success in terms of mitigating coexistent forms of obesity and undernourishment over the past 20 years. Levels of undernourishment decreased substantially in the rapidly expansionist archetype and moderately in the expansionist archetype, by median rates of -3.27% (3.26%) and -1.77% (4.21%) annually, respectively (Figure 4). This pattern reveals remarkable progress, for instance, towards ending hunger in countries that have been most affected by food insecurity – the prevalence of undernourishment in 1995 in RETA and ETA countries was 24.7% (20.4%) and 18.7% (19.1%), respectively. The rate of obesity increase, however, surpassed the rate of undernourishment decrease in all archetypes. Increases in obesity were steepest in RETA, with growing prevalence of 5.04% (1.44%) per year, followed by the ETA with 3.34% (2.19%) and 2.42% (0.97%) for CTA. Note that RETA starts from a lowest base, with obesity prevalence in 1995 in RETA, ETA and CTA respectively as 3.25% (2.6%), 8.75% (1.45%), and 15% (5.7%).

These paradoxical trends in undernourishment and obesity reveal an important challenge for the majority of countries globally, since 87% of nations currently experience double or triple burdens of malnutrition (revealed by different combinations of overweight & obesity, underweight, and/or micronutrient deficiency - FAO et al., 2019). This is particularly relevant to countries that were not able to eliminate the substantial health and social challenges from food insecurity, such as those in South America, Sub-Saharan Africa, and South-western and South-eastern Asia (Figure 2). Simultaneous increases in obesity indicate high-levels of inequality in access to food and can overburden health systems in the pursuit of adequate prevention and treatment of non-communicable diseases attributable to dietary risks (Development Initiatives, 2020). An additional consideration is the systemic effects of an increasingly interconnected global food system, whereby rapid increases in both food imports and exports across the globe suggests a pattern of increased trade dependency. Food imports increased for all archetypes by roughly 10% annually (the highest rates of change recorded across all metrics), accompanied by an equivalent increase in food exports (highest values in RETA; Figure 3). This pattern in food trade can be seen as a double-edged sword. It can bring efficiency through comparative advantage, monetary gains for actors involved in global markets, and food diversity for many globally (Clapp, 2017). On the other hand, trade dependency has also been suggested to be associated with potential systemic risk to environmental and economic shocks (especially in major export-oriented countries with less diversity in food production - Kummu et al., 2020), with consequent threats to populations most vulnerable to price fluctuations, seasonal shortages, and reduced nutritional quality of food baskets (Davis et al., 2021).

Socioeconomic indicators

The rate of change of GDP socioeconomic indicators tended to be independent from the transformation archetypes (Supplementary Tables S6 and S7). All transformation archetypes showed a general trend of increase in GDP per capita both for nominal and purchasing power parity: RETA = 3.5% (10.3%) and 2.5% (20.4%), ETA = 1.9% (13.1%) and 2.1% (10.2%), and CTA = 2.8% (9.5%) and 2.1% (7%). In terms of human development category (i.e., low, medium, high, or very high human development), RETA expressed, simultaneously, the biggest proportion of countries categorized as low human development in 1995 (n=17; 81%) and the lowest ratio of improvement in human development category by 2015 (n=7; 33.3%). ETA had a substantial proportion of countries in low and medium human development category at the beginning of the analysis (n=25 and n=20; 53% and 42.6%, respectively) and around two thirds of these countries showed improvements in their category at the end (n=30). CTA, finally, exhibited the highest proportion of countries in high and very high human development categories in 1995 (n=18 and n=19, 27.3% and 28.8%, respectively) and was tied with ETA in terms of improvement of category by 2015 (n=41, 62%). The Human Development Index was an exemption to this general trend in socioeconomic metrics, revealed by a steeper increase in RETA than in ETA, followed by CTA: median of 1.57% (0.95% interquartile range), 0.97% (0.52%), and 0.67% (0.39%), respectively (Supplementary Tables S6 and S7). Although only 135 countries were measured for this metric, the proportion falling into the three respective archetypes was broadly equivalent to the full dataset: RETA = 21 (15.5%), ETA = 48 (35.5%), and CTA = 66 (49%) countries.

Economic development, traditionally measured by income level (i.e., low, lower-middle, upper-middle, and high-income countries stratified by gross national income per capita), was also found to be in a converse trajectory of change to RETA and ETA. Similar to the pattern for human development category, RETA not only had the highest proportion of low-income countries in 1995 (n=19, 73%), but also only 8 out of 26 countries (30.8%) ameliorated their income category by 2015. Conversely, CTA displayed the highest ratio of upper-middle and high-income countries early in the analysis (n=13 and n=27, 20.6% and 37.5%, respectively) and, simultaneously, showed the largest improvement in income category (n=37, 51.4%). The ETA had a substantial share of countries in the low and lower-middle-income category in 1995 (n=30 and n=27, 47.6% and 42.8%, respectively) and 29 out of 63 countries (46%) improved their condition by 2015. Overall, this means that expansionist traits exhibited by archetypes of change in global food systems did not broadly reflect increased incomes (i.e., GDP per capita) and, in more practical socioeconomic terms (i.e., comparable categories of gross national income per capita), tended to be associated with persistent socioeconomic disadvantages despite increased agricultural productivity.

Relevance for research and practice

Our findings add quantitative evidence to recent qualitative assessments on food systems transformation to show that despite increases in yields and productivity, national food production and supply across the countries investigated are in general failing to reorient their trajectories towards the ability to nourish people with healthy and sustainable diets per unit input (Bahadur et al., 2018; Benton & Bailey, 2019; Poore & Nemecek, 2018; Springmann, Clark, et al., 2018; Willett et al., 2019). Our study reveals the extent of the historical and current trade-offs between food system productivity and more holistic measures of food systems sustainability and success in delivering environment, health, and other social outcomes, including how this relationship diverges across countries.

Our study was designed to expand the assessment of emerging patterns in global food systems beyond linear assumptions of change over time or multidimensional analysis of single surrogate outcomes. We consequently paid crucial attention in the selection of metrics to quantify links amongst agricultural productivity, environmental pressures, malnutrition, and socioeconomic wellbeing. We analysed key food system structure metrics that enable a nuanced understanding of multiple aspects of agricultural production in comparison to single metrics (e.g., ‘agricultural value added per worker’). In terms of outcomes, for instance, we expressed malnutrition outcomes by prevalence of obesity and undernourishment, which are conclusive endpoints of population health and nutritional status.

Our typology explicitly links coexistent changes in food systems structure and outcomes over time and, thus, can provide a complementary and timely diagnosis to other typologies drawn upon share of dietary energy (Fanzo et al., 2020), diversity of food supply (Bentham et al., 2020; IFPRI, 2015), and the literature of food systems transformations. In addition, our study provides longitudinal insights to important cross-sectional advancements in the scholarship. Marshall *et al.* (2021), after an extensive search of food systems typologies in the literature, investigated key metrics that lie between food productivity and nutritional outcomes, such as food environments (e.g., quantity of supermarkets and diversity of food) and consumer-related factors (e.g., percentage of urban population). They observed five food system types, with salient similarities to our findings: rural and traditional; informal and expanding; emerging and diversifying; modernizing and formalizing; and industrial and consolidated. Collectively, these categories evince the potential to serve as an useful tool to simplify some of the complexity of global food systems with comparable models and can assist in the initial steps to design strategies and policies for sustainable and healthy transitions.

Reflections on our approach

Our typology is one of ‘requisite simplicity’ (Stirzaker et al., 2010) — we have uncovered important longitudinal differences across the globe spanning multiple countries and contrasted these findings with paradigms of productivity (i.e., production output per unit of input) and of systems efficiency and sustainability (i.e., the social, environmental, and economic links to optimized productivity). In doing so we have followed geopolitical boundaries and so excluded potential within-country diversities. This might be considered a limitation of our approach as it masks meaningful heterogeneity in food systems. However, we argue that by focusing on key geopolitical units, our typology can be used to inform national policymaking and international governance to leverage change in food systems (Abson et al., 2017). Secondly, we quantify and report our results under a general umbrella of agricultural production. We do not consider the details of different food types or groups (e.g., distinct structure and social-ecological outcomes amongst crops, livestock, or horticultural systems) because: a) previous studies are already available for this level (Poore & Nemecek, 2018; Springmann, Clark, et al., 2018); and b) in this study, we want to provide a holistic, quantitative, and complementary diagnosis of global food systems diversity to the body of literature in food systems transformations. Thirdly, the sample metrics included in our model and its period of assessment between 1995 and

2015 are a result of limitations in the availability and quality of the datasets explored. Other relevant metrics to our research problem were either excluded from our study due to insufficient observations (e.g., pesticide use) or unavailable for a reasonably long time to allow a longitudinal analysis (e.g., food loss & waste). Broader methodological reflections are elaborated in the Supplementary materials (Methodological reflections).

Despite these limitations, we have identified 'progress' in many metrics of food systems across a vast number of countries globally in the past two decades. However, this notion of progress, narrowly defined in terms of higher agricultural output or improved cost-efficiency of production, was broadly independent from (or even counter to) the ability of global food systems to mitigate coexistent forms of malnutrition, pressures to planetary boundaries, or socioeconomic vulnerabilities. By quantifying the contrasts between development pathways across national food production and trade settings, we can track the empirical change of dynamic social-ecological interactions. These distinctions are valuable because they: a) show patterns of incoherence between expected food system provisions (i.e., goals and aspirations) and what they actually deliver more explicitly (Poore & Nemecek, 2018; Springmann, Wiebe, et al., 2018); and b) reveal multiple pathways for food system development, which highlights that the future is not deterministic.

Conclusions

Our analysis shows that under current trajectories of change, dominant paradigms focusing on higher yields alone are not only insufficient to achieve consensual global goals (e.g., ending hunger or limiting global warming to 1.5°C - Pradhan et al., 2017) but they could even hamper the attainment of other goals indirectly (e.g., health system costs for reasonable prevention and treatment of diet-related non-communicable diseases - Development Initiatives, 2020). Our conceptual design and quantitative assessment further reveal a novel entry point for exploring the intertwined challenges of sustainable food systems, in particular for a better understanding of temporal dynamics. Given the long term trajectories revealed, a step change in strategies is likely needed to make progress that includes improved resilience of supply chains, sustainable agriculture (e.g., no-till and precision agriculture, reduced reliance on synthetic fertilizers) and educational, economic, and environmental policies towards more plant-based diets (Nyström et al., 2019; Poore & Nemecek, 2018; Springmann, Clark, et al., 2018).

Our systemic approach helps to inform multiple decision-making jurisdictions about the systemic nature of increasingly interconnected global food supply chains and, at the same time, to invite innovative reflections for envisioning, implementing, and evaluating sustainability transitions in food systems (Oliver et al., 2021). These intertwined relations inherently raise questions about equity and power dynamics across nations, which can impair collaboration and constrain systems transformation in decision-making platforms if disregarded (Dornelles et al., 2020). Our assessment on pace, direction, and scale of multiple coexistent metrics enables an examination of ongoing and long-term patterns often neglected in favour of ‘safer’ judgments about isolated, individual risks in the short-term. Thus, our typology can help to reveal early stages of opportunities and constraints related to leverage points to sustainability transformations.

Essentially, the interdependence across global food systems requires policies consistent with their empirical trajectories and tailored for different transformation archetypes. Acknowledging the synergies between malnutrition, environmental, and social issues is key for sustainable development of food systems, in alignment with heterogeneity at smaller scales (i.e., within-country diversities). Finally, more research is needed to uncover comprehensive ‘watchpoints’ where there are adequate data to quantify shifts in trajectories, in response to targeted efforts to meet Sustainable Development Goals, as they apply to food systems at global, national and regional scales.

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Declarations:

Funding: The funders of the study had no role in study design; in the collection, analysis, and interpretation of data; in the writing of the report; and in the decision to submit the paper for publication.

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Data and code availability: The authors declare that the data supporting all figures of this study are available within the paper and its supplementary materials. The data that support the findings of this study are available from: the Food and Agriculture Organization of the United Nations (available from http://www.fao.org/faostat/en/#data), World Development Indicators, from the World Bank (available from https://databank.worldbank.org/source/world-development-indicators), SDG Indicators database, from the United Nations (available from https://unstats.un.org/sdgs/indicators/database/), Climate Analysis Indicator Tool, from the World Resource Institute (available from https://www.climatewatchdata.org/ghg-emissions?sectors=512%2C514), the International Labour Organization (available from https://ilostat.ilo.org/data/), the International Fertilizer Association (available from https://www.ifastat.org/databases), and the United States Department of Agriculture (available from https://www.ers.usda.gov/data-products/international-agricultural-productivity/). Furthermore, the authors declare that the scripts supporting all figures and results of this study are described in the Supplementary materials (Supplementary Table S8) and accession codes are deposited into a public repository: [*Add URL here if accepted*].

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Figure and Table: Titles and legends

Box 1

Title: Characteristics of the transformation archetypes in global food systems.

Figure 1

Title: Simplified framework of structure and outcome metrics and their connections in our integrative model.

Legend: The structure metrics are widely used as measurements of performance of food production (cf. paradigm of productivity), whilst the combination of structure and outcome metrics were used in this study to assess their links to productivity (cf. paradigm of systemic efficiency).

Figure 2

Title: Transformation archetypes affecting national food production and supply of 161 countries from 1995 to 2015.

Legend: Rate of annual change for structure metrics (on the top) and for outcome metrics (on the bottom) are measured by compound annual change rate (median, % / year). Lowercase letters 'a', 'b', and 'c' besides arrows indicate significant differences from the rapidly expansionist transformation archetype (baseline reference expressed by 'a') for each metric at $p < 0.05$ (e.g., 'a', 'a', and 'a' denote no difference across transformation archetypes whilst 'a', 'b', and 'c' indicate that all are different). Arrows pointing up show increasing trends, arrows pointing down show decreasing trends, whilst white rectangles indicate no change over time. The colouring scheme expresses magnitude of the rates of change: black colour designates rapid change (≥ 3% and ≤ -3%), dark grey colour reveals intermediate (1.5% to 3% and -1.5 to - 3%), grey colour specifies mild (0.5% to 1.5% and -0.5% to -1.5%), whilst white colour represents slow change (0% to 0.5% and 0% to -0.5%). Abbreviations: TFP – Agricultural Total Factor Productivity; GHGE – greenhouse gases emissions; AFOLU – Agriculture, Forestry and Other Land Use.

Figure 3

Title: Global trends in structure metrics across transformation archetypes in global food systems of 161 countries from 1995 to 2015.

Legend: Values are expressed by medians, coloured boxplot hinges indicate the range between the 1st and 3rd quartiles, whiskers indicate 1.5 times the distance from the nearest hinge, and individual points are data observations beyond the extremes of the whiskers. Horizontal dashed lines represent absence of change (i.e., 0% annual change rate). Lowercase letters 'a', 'b', and 'c' besides arrows indicate significant differences from the rapidly expansionist transformation archetype (baseline reference expressed by 'a') for each metric at $p < 0.05$ (e.g., 'a', 'a', and 'a' denote no difference across transformation archetypes whilst 'a', 'b', and 'c' indicate that all are different). The transformation archetypes are coloured as: rapidly expansionist in vermillion, expansionist in green, and consolidative in blue.

Figure 4

Title: Global trends in outcome metrics across transformation archetypes in global food systems of 161 countries from 1995 to 2015.

Legend: Values are expressed by medians, coloured boxplot hinges indicate the range between the 1st and 3rd quartiles, whiskers indicate 1.5 times the distance from the nearest hinge, and individual points are data points beyond the extremes of the whiskers. Horizontal dashed lines represent absence of change (i.e., 0% annual change rate). Lowercase letters 'a', 'b', and 'c' besides arrows indicate significant differences from the rapidly expansionist transformation archetype (baseline reference expressed by 'a') for each metric at $p < 0.05$ (e.g., 'a', 'a', and 'a' denote no difference across transformation archetypes whilst 'a', 'b', and 'c' indicate that all are different). The transformation archetypes are coloured as: rapidly expansionist in vermillion, expansionist in green, and consolidative in blue. Abbreviations: GHGE – greenhouse gases emissions; AFOLU – Agriculture, Forestry and Other Land Use.